Rainbow refractometry with a tailored incoherent semiconductor laser source

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The authors demonstrate within a metrology experiment the applicability of a recently proposed temporally incoherent semiconductor laser source which relies on nonlinear dynamics. The realized spectrally broadband emission with an output power of 110 mW and a coherence length of only 120 μm is used in a rainbow refractometry experiment for sizing of liquid droplets, representing an important problem in industrial processes. The observed emission characteristics are attractive for implementation of modern imaging and metrology techniques which are based on the properties of well-directed, temporally incoherent light. © *2006 American Institute of Physics*.
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Optical metrology techniques are widely used for investigation and control of various processes in science and technology.[1] The potential for noninvasive sensing is probably the most striking advantage, which is complemented by the possibility for realization of remote sensing and fast acquisition of information. These benefits are particularly attractive for medical imaging and applied metrology in process control. Such applications place high demands on measurement resolution and dynamic range and, consequently, on the properties of the implemented light sources. Bright, low-noise sources with good beam properties are often required for applied optical metrology; hence coherent laser sources have become favored light sources. In particular, semiconductor lasers (SLs) are widespread in this field because of their attractive emission properties, their small dimensions, and their high wall-plug efficiency.[1] In some applications, interference effects of coherent light can, however, constrain the accuracy of measurement. In such applications, well-directed incoherent light can be advantageous. Two such examples are coherence tomography[2] and fiber optics gyroscopes.[1] Hence, there is a growing interest in the development of appropriate bright incoherent light sources (ILSs) with good beam properties that are also practical, compact, and cost effective.

In this context, we demonstrate that a recently proposed simple and versatile SL system[3] can serve as an ILS in practical metrology. We explore the optimized spectrally broadband emission properties of the SL source in rainbow refractometry. The obtained results demonstrate that the SL source is an attractive alternative for realization of an ILS.

Recently, we have demonstrated that the spectral bandwidth of semiconductor lasers can be substantially enhanced by using the nonlinear dynamical properties of a well-designed external cavity configuration.[3] A schematic of the experimental realization of such a SL source is presented in the upper half of Fig. 1. In the lower half of the figure, we have sketched the rainbow refractometry experiment which we use to test the performance of our SL source. The implemented SL is a commercially available 1.6 mm long ridge waveguide Fabry-Pérot SL which emits at a center wavelength of 785 nm. The emitted light is collimated by a lens (L), partially back reflected by a mirror (M), and reinjected into the SL after the round trip time τ in the external cavity with the phase difference $\Delta\Phi=\Phi(t)-\Phi(t-\tau)$. A key for generation of broadband emission consists in the realization of a resonance condition between the fundamental frequency of the laser cavity and the external cavity, both being of comparable order of magnitude. This can enhance coupling between the longitudinal laser modes (LMs) allowing for spectrally broadband emission.[3] We set the ratio between the length of the external cavity ($L_{EC}=14.8$ mm) and the optical length of the SL cavity ($L_{SL,opt}=5.92$ mm) precisely to 2.5, for which we can achieve good coupling of the LMs. For these conditions, the key parameters which determine the emission properties of the SL are the delay time τ, the pump current I_{dc} of the SL, the feedback ratio r, and the feedback

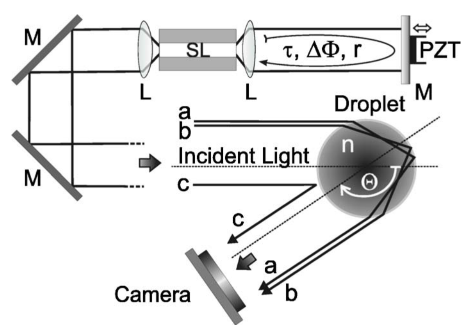

FIG. 1. Schematic of the incoherent semiconductor laser source and the rainbow refractometry experiment.

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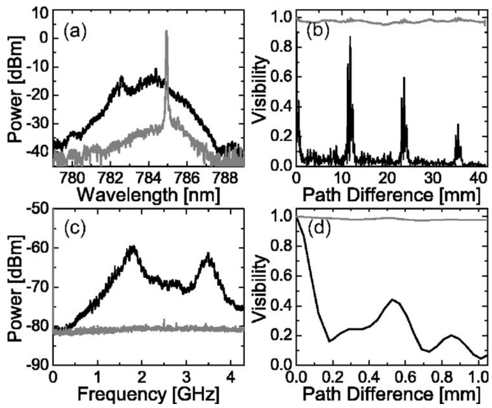

FIG. 2. Characteristics of the SL source for stable (gray) and broadband (black) emission. Panel (a) shows the optical spectra for both cases. The corresponding visibility functions and a zoom thereof are presented in panels (b) and (d). The rf spectra of the intensity dynamics are shown in panel (c).

phase $\Delta\Phi$ being a 2π-cyclic parameter. The feedback ratio r is defined as the ratio between the power of the feedback and the emitted light, $r=P_{fb}/P_{out}$. We use $\Delta\Phi$ as the control parameter, which we change by shifting the mirror on a subwavelength scale with a piezoelectric transducer. The other parameters are kept constant: $r=0.16$, $\tau=98.7$ ps, and the pump parameter $p=I_{dc}/I_{th,sol}=3.3$, with $I_{th,sol}=46$ mA being the threshold current of the solitary SL. We analyze the intensity dynamics of the emitted light with a 12 GHz photodetector and a rf spectrum analyzer with 21 GHz bandwidth. Furthermore, we characterize the spectral properties using a grating spectrum analyzer (50 pm resolution) and measure the visibility properties with an interferometric spectrum analyzer (8 pm resolution).

In our previous work,[3] we have shown that $\Delta\Phi$ is an excellent control parameter which allows for gradual adjustment of the emission properties. Here, we benefit from this feature using two characteristic states of emission. Depending on $\Delta\Phi$, we can either adjust for stable emission on one LM to which we assign the phase value to be $\Delta\Phi_{stab}$, or we can adjust for spectrally broadband (BB) emission for slightly reduced $\Delta\Phi_{BB}=\Delta\Phi_{stab}-0.4\pi$ rad. This is shown in Fig. 2, which summarizes the emission properties of both states. Panel (a) depicts the optical spectra for both cases. The gray spectrum, obtained for $\Delta\Phi_{stab}$ exhibits single mode emission with a sidemode suppression of more than 30 dB. In contrast to this, the spectrum for $\Delta\Phi_{BB}$, shown in black, gives rise to emission in a remarkable high spectral range of about 7 nm. For this state, we measure an output power of 110 mW and good beam properties with $M^2<1.2$. This attractive spectrally broadband emission is of dynamic origin, which becomes evident from the corresponding rf spectrum of the intensity dynamics, represented by the black line in panel (c). We find a continuous rf spectrum with a bandwidth exceeding 4 GHz representing the underlying chaotic dynamics. The comparison with the flat rf spectrum for stable emission (gray line) discloses that the low frequency part of the rf spectrum is at the noise floor of the detection at −82 dBm. This implies that the average power of the SL source for this emission state exhibits low relative intensity noise on the relevant time scales for technical applications. We note that the broadband emission state is robust despite relying on dynamical instabilities. In this regard, the dynamically induced low coherence properties of the light source are of interest to low coherence metrology. To quantitatively characterize the coherence properties, we measure the visibility functions for both emission states, which are presented in panel (b).

The visibility function for stable emission, shown in gray, is almost constant at maximum visibility. This property impedes estimation of the coherence length via determination of the falloff of the function. Nevertheless, we were able to determine a coherence length of $L_{coh}=7.8$ m by measuring the optical linewidth with a Fabry-Pérot scanning interferometer. In contrast to this, we find conspicuously different visibility properties for spectrally broadband emission, which are presented in black. The visibility function exhibits a fast fall-off to values below $1/e$ within only 120 μm, as it can be seen in the zoom in panel (d), recorded for the same conditions. From the large range visibility function in panel (b), we also identify recurrent peaks with high visibility at multiples of $2\times L_{SL,opt}=11.9$ mm. These peaks originate from remaining correlations between the LM, an effect that might be diminished by reduction of the facet reflectivity of the SL. However, this is not essential for implementation of many high-resolution metrology applications, since the achievable measurement resolution is essentially defined by the first falloff of the visibility function. To substantiate this claim we characterize the performance of the reported light source using rainbow refractometry.

In the rainbow refractometry experiment, we determine the size of a liquid droplet, which represents an important task in internal combustion engines, spray cooling, medicine, and applications in agriculture, to name only a few.[4] Rainbow refractometry is a noninvasive, optical measurement technique used to determine the temperature or size of droplets by analysis of the primary rainbow scattering. This information is contained in the angular intensity distribution of the scattered light.[5–7] Figure 1 illustrates the main contributions to the angular intensity distribution for the rainbow for second-order refraction. In principle, the required information can be accurately obtained by analysis of the detected far-field interference pattern between the sketched rays (a) and (b), which reveals so-called supernumerary arcs. For coherent illumination, however, which is often used in applications, the supernumerary arcs show additional modulation due to interference between the refracted light, rays (a) and (b), and the reflected light from the surface of the droplet, ray (c). This additional interference effect complicates the interpretation of the intensity distribution and, thus, determination of the desired information. In contrast, when the coherence length is shorter than the path length difference between the second-order refraction and the surface reflection, only the pure supernumerary arcs of the second-order refraction prevail. This simpler interference pattern allows for more accurate and simpler determination of the droplet size, as it is desired in industrial process control. Removing coherence too far, for example, by using a white light source, would eliminate the intensity modulation resulting from the two-ray solution of the second-order refraction. Therefore, the coherence length of the light source must be non-negligible but sufficiently short. Consequently, rainbow refractometry can serve as an ideal example for testing the performance of our incoherent SL source.

In the experiment, we illuminate a water droplet with collimated light from the SL source. The water droplet is

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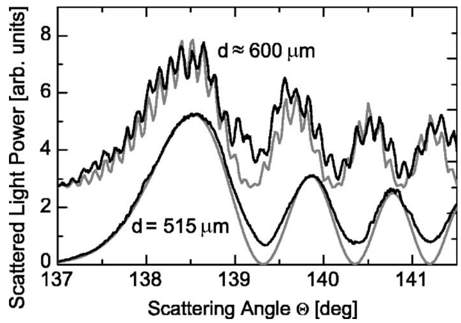

FIG. 3. Experimentally (black lines) and numerically (gray lines) obtained angular intensity distributions for rainbow refractometry with a water droplet for coherent and incoherent illuminations. The distributions for coherent illumination are shifted upward by three units.

trapped by an acoustic levitator, which can appropriately suspend spherical droplets with diameters between 400 μm and 1 mm. We illuminate the droplet with coherent light with $L_{coh}=7.8$ m and record the angular intensity distribution of the scattered light using a 12 bit charge-coupled device camera and a shutter time of 1 ms. Subsequently, we repeat the procedure for incoherent illumination with $L_{coh}=120$ μm. The experimental results are given by the black lines in Fig. 3. The upper black distribution corresponds to coherent illumination and has been shifted upward by three units to facilitate comparison with the measured distribution for incoherent illumination, represented by the lower black line. The comparison of both distributions reveals striking differences. For coherent illumination we find the unwanted interference structure (ripples) on top of the supernumerary arcs from second-order scattering, while we obtain a smooth intensity distribution without superimposed ripples for incoherent illumination. This smooth structure allows direct, accurate determination of the position of the supernumerary arcs which can be used to estimate the diameter of the droplet[5] to be $d=515\pm5$ μm. In contrast to this, for coherent illumination, complex and time-consuming numerical modeling based on the Lorentz-Mie theory[8] needs to be applied for proper estimation of the droplet size. To gain insight about the achievable accuracy for both methods, we have performed such demanding calculations and numerically varied the diameter of the droplet d until we achieve good agreement between the experiment and numerics. We have assumed a refractive index of $n=1.33$ and illumination by monochromatic light at a wavelength of 780 nm. The upper gray curve in Fig. 3 shows that fairly good agreement is achieved for a droplet size of $d\approx600$ μm, with an uncertainty of ±50 μm. Nevertheless, the calculations also show that, additionally to the time-consuming complex calculations, the achieved accuracy is substantially lower if compared to the result for incoherent illumination. To highlight the accuracy that can be achieved for incoherent illumination, we have also performed similar numerical calculations, but only considering second-order refraction in the model. The main result is presented by the lower gray distribution in Fig. 3, which shows excellent agreement between the experiment and the modeling for an assumed droplet size of $d=515$ μm, underlining the high accuracy of the experimentally estimated droplet size.

These results confirm that the realized chaotic SL source is a functional ILS, which can be applied for realization of modern metrology techniques. The light source combines many advantageous properties, such as well-directional light, high output power of 110 mW, good beam properties with $M^2<1.2$, and controllable short coherence length of $L_{coh}\approx100$ μm. We emphasize that the functional principle of the realized ILS can be transferred to other SLs so that ILSs can be realized in a broad spectral range between the UV and mid-IR. Furthermore, reduction of the coherence length to the order of $L_{coh}\approx50$ μm is expected to be possible via optimization of the laser and feedback parameters. In this regard, this compact and cost efficient high-power ILS represents an attractive alternative for rainbow refractometry, if compared to the established costly pulsed laser sources or the feedback sensitive superluminescent light emitting diodes, which only offer comparably low output powers.

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